Letter submitted to **Nature**, November 22, 1995:

The X-ray Evidence that the 51 Peg Companion is a Planet

51 Pegasi is a nearby G2-3 V star' which is similar[2] to the Sun. Observers have recently detected[3] and confirmed[4,5] that 51 Peg has sinusoidal radial velocity variations with a period of 4.2 days and amplitude of 59 m/s. The radial velocity, if due to orbital motion around the system center-of-mass, implies a minimum companion mass of 0.47 Jupiter masses[3], which results from the assumption that the inclination angle of the system is 90° from the line of sight. We argue that the X-ray luminosity of the 51 Peg system implies that the unseen companion is a planet, independent of any assumption about the inclination angle.

The argument to infer the system inclination angle and companion mass can be stated as follows: Assume that the 51 Peg rotational inclination angle, i_r, and the system inclination angle, i, are nearly equal as in the solar system. The measured[6] rotational velocity of51 Peg, $v_r \sin i_r$, is 1.7 ± 0.8 km/s. 51 Peg is classified as a star with a weak chromosphere - the normalized Ca 11 emission strength is slightly less than that of the Sun. A statistical relation between Ca II emission strength and Rossby number for solar-type stars leads to a 29.7 day estimate[8] for the rotation period. The observed V-R = 0.54, V = 5.49, and the surface flux relation[9] imply an angular diameter of 0.714 milliarcsecs, and a radius of 7.2x 1010 cm for a distance[10] of 13.5 pc. This radius and the 29.7 day rotational period result in v, = 1.8 km/s, which taken with the measured value of $v_r \sin i_r$, lead to i, ~ 90°. With $i \sim i_r$ the companion is near the minimum mass, and it is a planet.

Unfortunately, this determination of i depends on a number of assumptions and a $v_r \sin i_r$ measurement near the detection limit. If i is smaller than 90°, then the mass of the companion is more than the minimum mass. What are the possibilities that the inclination is close to 0°, and the companion is a low-mass star? Optical spectroscopic observations of51 Peg[1,11] rule out the possibility that the companion is anything larger than a dim, late-type dwarf, since there are no spectral signatures of a brighter star. An M dwarf, for example, which might be 100 times dimmer than 51 Peg could be spectroscopically hidden. A search in a spectroscopic binary star catalog[12] indicates that there are no known binaries consisting of G and M dwarfs with --4-day periods, either because none exist (a currently unexplained possibility), or because such systems are difficult to detect and identify.

There are a number of known binary systems containing late-type stellar members with orbital periods similar to that of51 Peg. These systems all share three common, related attributes: (1) the orbital and rotational periods are nearly equal and the systems arc "phase-locked" due to either turbulent viscosity[13] or large-scale hydrodynamic forces[14,15]; (2) the stars exhibit strong chromospheres; and (3) the systems are relatively luminous X-ray sources. 'J'he RS CVn systems are an example of these binaries. We searched for all known binaries[12,16,17] containing a combination of F through M stars and and periods from 2-6 days. We found 32 examples of such systems with identified components, all of which have X-ray luminosities in the range, L_x = 7 x 1028 -2 x 10^{32} erg/s, strong chromospheres, and are phase-locked or nearly phase-locked (if the rotational periods are known).

51 Peg was observed by the ROSAT observatory[18] for 12503 s on 28-29 December, 1992. X-ray emission was detected[19] with L_x =- (6.4± 1.3)x 10^{26} erg/s. This value is typical of an isolated G dwarf

like the Sun[20] and is least 100 times less than that from the close binaries discussed above. This low value for the X-ray emission supports the derivation that the rotational period of51 Peg is 29.7 days, and not equal to its 4.2-day orbital period. This last statement allows one to evaluate the competing theories of orbital and rotational synchronization, both of which predict that the time for synchronization decreases with increasing companion mass. Turbulent viscosity[13] places an upper limit of- 10 Jupiter masses on the companion if the 51 Peg system age is > 10^9 y, i.e., similar to the Sun. The hydrodynamic theory[15] apparently underestimates the synchronization time scale since51 Peg should be phase-locked even with the minimum companion mass.

In conclusion, the 51 Peg system shares none of the common attributes of binary stars with similar orbital periods. Its low X-ray luminosity and its weak chromosphere suggest, independent of the system inclination angle, that 51 Peg is not a member of a binary stellar system, and that its companion is a planet.

Steven H. Pravdo
California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive, M.S. 306-438
Pasadena, CA 91109, USA

Nicholas E. White, Lorella Angelini, and Stephen A. Drake
Laboratory for High Energy Astrophysics
Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, MD 20771, USA

Robert A. Stern
Solar and Astrophysics Laboratory
Lockheed Palo Alto Research Center
3251 Hanover Street
Palo Alto, CA 94304, USA

The rc.search described herein was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration

1. Houk, N. 1995, IAU Circ No. 6253
2 Hardorp, J. 1980, A&A, 91,221
3 Mayor, M & Queloz, D. 1995, IAU Circ. No 6251
4 Marcy, G. & Butler, P. 1995. IAU Circ. No 6251
5. Noyes, R et al 1995, IAU Circ. No. 6251
6. Soderblom, D R 1982, ApJ, 263,239
7. Soderblom, D R et al 1993, ApJS, 85,31 S
8. Noyes, R et al 1984, ApJ, 279,763
9. di Benedetto, G P. & Rabbia, Y. 1987, A&A, 188, 114
10. Hoffleit, D. & Jaschek, C. 1982, 'The Bright Star Catologue," (Yale University Press)
11. McWilliam, A, 1990, ApJS, 74, 107S
12 Batten, A H et al 1989, "Eighth Catalogue of the Orbital Elements of Spectroscopic Binary Systems," Pub of the Dominion Astr Obs and L'Obs Federal D'Astr., NRC No. 29684
13. Zahn, J -P. 1977, A&A, 57,383
14. Tassoul, J.L, 1987, ApJ, 322,856
15. Claret, A et al 1995, A&A, 299,724
16. Strassmeier, K G. et al 1993. A&AS, 100.173
17. Duquennoy, A & Mayor. M 1991, A&A, 248,485
18. Trümper, J. 1983, Adv. Space Res., 2, No 4, 241
19. Zimmermann, H U., 1994, IAU Circ No 6102
20. Stern, R A et al 1981, ApJ, 249,647